The more extreme nature of North American monsoon precipitation in the Southwestern United States

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Invited Presentation
WRRC Brown Bag
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Outline

• Monsoon weather hazards
• Severe weather monsoon meteorology
• High resolution modeling approach, performance
• Changes in atmospheric environment, extreme weather
• Information translation
• Concluding points

Acknowledgement: Funding from Strategic Environmental Research and Development Program (SERDP), Resource Conservation and Resiliency (Project RC-2205).
Monsoon Severe Weather Hazards
Effects of Anthropogenic Climate Change?

Forecast concerns
• Precipitation amount
• Precipitation intensity
• Wind gusts (outflow boundaries)
• Spatial location
• Timing
Phoenix Dust Storm: 5 July 2011
UA Project Team: Hsin-I Chang, Tim Lahmers (M.S.), Thang Luong (Ph.D.), Carlos Carrillo (Ph.D.), Megan Jares (M.S.), Jeremy Mazon (M.S.), Jennifer Stutler (M.S.), Bill Cassell (M.S.), Mike Leuthold
# 25th OWS Terminal aerodrome forecast (TAF) Weather Watch and Warning Criteria

## Weather Watches

<table>
<thead>
<tr>
<th>Watch Type</th>
<th>Criteria</th>
<th>Area Affected</th>
<th>Desired Lead Time</th>
<th>Mission Impact (other than those stated in AFMAN 15-129)</th>
<th>Issued By</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tornado</strong></td>
<td>Tornado or Funnel Cloud</td>
<td>Aerodrome (5NM)</td>
<td>As potential warrants</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Damaging Winds</strong></td>
<td>Winds &gt;= 50 kts</td>
<td>Aerodrome (5NM)</td>
<td>As potential warrants</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Hail</strong></td>
<td>&gt;= ¼ inch</td>
<td>Aerodrome (5NM)</td>
<td>As potential warrants</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Freezing Precipitation</strong></td>
<td>Any</td>
<td>Aerodrome (5NM)</td>
<td>As potential warrants</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Heavy Snow</strong></td>
<td>&gt;= 2&quot; in 12 hrs</td>
<td>Aerodrome (5NM)</td>
<td>As potential warrants</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Heavy Rain</strong></td>
<td>&gt;= 2&quot; in 12 hrs</td>
<td>Aerodrome (5NM)</td>
<td>As potential warrants</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Lightning</strong></td>
<td>Potential within 5 nm</td>
<td>Aerodrome (5NM)</td>
<td>30 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Lightning</strong></td>
<td>Within 5 nm of Aerospace Maintenance and Regeneration Group (AMARG)</td>
<td>Aerodrome (5NM)</td>
<td>30 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
</tbody>
</table>

## Weather Warnings

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<tr>
<th>Warning Type</th>
<th>Criteria</th>
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<th>Mission Impact (other than those stated in AFMAN 15-129)</th>
<th>Issued By</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tornado</strong></td>
<td>Tornado or Funnel Cloud</td>
<td>Aerodrome (5NM)</td>
<td>0 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Damaging Winds</strong></td>
<td>Winds 35-49 kts</td>
<td>Aerodrome (5NM)</td>
<td>60 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Strong Winds</strong></td>
<td>Winds 35-49 kts</td>
<td>Aerodrome (5NM)</td>
<td>60 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Hail</strong></td>
<td>&gt;= ¼ inch</td>
<td>Aerodrome (5NM)</td>
<td>60 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Freezing Precipitation</strong></td>
<td>Any</td>
<td>Aerodrome (5NM)</td>
<td>90 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Heavy Snow</strong></td>
<td>&gt;= 2&quot; in 12 hrs</td>
<td>Aerodrome (5NM)</td>
<td>90 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
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<td>90 minutes</td>
<td>OWS</td>
<td>OWS</td>
</tr>
<tr>
<td><strong>Lightning</strong></td>
<td>Within 5 nm of Runway Complex</td>
<td>Aerodrome (5NM)</td>
<td>Observed</td>
<td>WF</td>
<td>WF</td>
</tr>
<tr>
<td><strong>Lightning</strong></td>
<td>Within 5 nm of AMARG</td>
<td>Aerodrome (5NM)</td>
<td>Observed</td>
<td>WF</td>
<td>WF</td>
</tr>
</tbody>
</table>

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**NOTES:**

- **ALL OBSERVED WEATHER WARNINGS AND ADVISORIES WILL BE ISSUED BY THE WEATHER FLIGHT DURING REGULAR DUTY HOURS. OWS WILL ISSUE OBSERVED WARNINGS/ADVISORIES WHEN THE WF IS NOT ON DUTY.**

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**NOTE:** 355 OSS/OSW and/or DMAF/CP will ensure these WWA criteria are sent to the NAOC POC.
Convection Permitting Models (CPMs)

**Weather forecasting**
- Weisman et al. 1997
- Done et al. 2004

**Climate**
- Langhans et al. 2012

**CPM grid spacing ≤ 4 km**

**ECMWF**

**GCMs**

**RCMs**

**CPMs**

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*Courtesy Andreas Prein*
What are the prerequisite meteorological conditions for strong monsoon thunderstorms?
Thermodynamic Criteria: Heat + Moisture

**Atmospheric Instability**

Cool the atmosphere aloft, warm atmosphere below
Facilitates development of vertically developed, cumuliform clouds

*Convective available potential energy (CAPE)*

**Atmospheric moisture**

Upper-level moisture: from easterly flow aloft
Low-level moisture: typically from surges of moisture from Gulf of California

*Column integrated precipitable water (PW)*
Monsoon Thunderstorms in Arizona

Forced by the diurnal mountain valley circulation
Form over the mountains during late morning to early afternoon
Reach mature stage by about mid-afternoon.

(Photo taken around 3pm)

Monsoon thunderstorms at Kitt Peak at mature stage with gust fronts.
Dynamic criteria

Monsoon ridge positioning
+ Upper-level disturbance (inverted trough)
+ Gulf surge = Large-scale upward motion
+ Vertical wind shear
+ Influx of low level moisture
Inverted trough: Favors upward motion and vertical wind shear
Convective organization and propagation

Convective clouds form over the mountains in the morning.

By afternoon and evening storms propagate to the west towards the Gulf of California where they can organize into mesoscale convective systems if there is sufficient moisture and instability.

It’s likely that a resolution less than 5 km is necessary to represent this process correctly in regional models. Global models pretty much fail.

Nesbitt et al. (2008)
Conditions for enhanced monsoon thunderstorms
NAME IOP 2: July 2004

An inverted trough (X) traveling around the monsoon ridge.

Low level-moisture surging up the Gulf of California

RESULT

Thunderstorms which originate on the Mogollon Rim intensify and move westward toward low deserts and the Colorado River Valley.
Mesoscale convective system associated with 5 July 2011 Phoenix dust storm

http://cimss.ssec.wisc.edu/goes/blog/archives/8409
Difference in WRF model simulated radar reflectivity for NAME IOP2 case: 3 UTC 14 July 2004
Vertical cross section through model depth from Sierra Madre Occidental to Gulf of California at 29.5°N

Wind vectors scale with ratio of 10:1 in horizontal to vertical.

Cassell et al. (in revision)
Methodological approach using regional convective-permitting modeling

Select CMIP3 and 5 models & global reanalysis 1-2.5° resolution

Baseline WRF long term regional climate model simulations for historical and future periods 35-50 km resolution

High resolution numerical weather prediction type simulations 2.5 km resolution

Long-term dynamical downscaling as RCM

Simulate identified severe weather events in RCM simulation

Radar reflectivity of simulated organized convection in Arizona
Daily Average Precipitation
 Modeled vs. Observations

Timing of Peak Convective Rainfall
Model versus Observations

High resolution model (2.5 km)
Coarse resolution model (35 km)

Observations

Peak Rainfall (LT)
5 am – 11 am
11 am – 5 pm
5 pm – 11 pm
11 pm – 5 am

Atmospheric Thermodynamic Conditions
Changes During the Last 30 Years

• Long-term modeled and observed increases in instability, precipitable water

• Changes can be attributed to (anthropogenic) climate change

Figure 2: JA differences in downscalned reanalysis (1980-2010 minus 1950-1979) for convective available potential energy (CAPE, J kg⁻¹) and precipitable water (PW, mm). Operational radiosonde sites indicated. (Jares et al., in preparation)
Atmospheric Dynamic Conditions
Changes over late 20th century

- The monsoon ridge has expanded
- Upper level disturbance displaced further south of the Southwest U.S.
- Less frequency of organized convective events in Arizona, but these events will be more intense
Statistical evaluation of precipitation extremes using Generalized Extreme Value Theory - GEV

- Conceptual idea is that extreme climate values (e.g. for precipitation or wind speed) in the tail of the distribution may not necessarily fit well to a theoretical PDF that applies to the whole lot of data.

- Solution is to fit generalized Pareto distribution, a peak-over-threshold method, to better describe the behavior in the tail (Rivera et al. 2014)

- Address statistical uncertainty by bootstrap resampling of the distribution.
Distribution of Extreme Daily Precipitation

Lower Frequency, More Intense Events

Notes: Historical past = 1950-1970; present day = 1990-2010
Results shown are for Phoenix, Arizona (PHX)

Luong et al. (2017, J. Appl. Meteor. and Climatol.)
Significant Changes: Extreme Precipitation

Largest Increase in Southwest Arizona

Note: 1950-1970 vs. 1990-2010

Luong et al. (2017, J. Appl. Meteor. and Climatol.)
Quantitative estimation of downdraft CAPE on Skew-T, log-P diagram (WAF class notes...)

Estimate downdraft strength by square root of 2 x DCAPE

Extract DCAPE from convective-permitting model simulations, analyze in a similar way to precipitation...
Extreme Downdraft Wind Speed

*Significant Change*

WRF-NCEP reanalysis model results

Note: Timeframes 1950-1970 vs. 1990-2010

Luong et al. (2017, J. Appl. Meteor. and Climatol.)
Precipitation

*Significant Change, Ensemble of Four CMIP3 and CMIP5 Global Climate Models*

Mean trend from model ensemble

Extreme trend from model ensemble

Note: Time period is 2021-2040 minus 1991-2010

*Castro et al. (in prep)*
Precipitation Intensity and Duration

*Significant Percentage Changes*

**WRF NCEP**
1990-2010 minus 1950-1970

**WRF CMIP Ensemble Average**
2021-2040 minus 1990-2010
Concluding Points

• There has been a long term increase in atmospheric moisture and instability in recent decades, due to anthropogenic climate change

• The more favorable thermodynamic environment is causing monsoon thunderstorms to be more extreme, though they are becoming less frequent

• High resolution atmospheric modeling is able to pinpoint southwestern Arizona as a local ‘hot spot’ where monsoon storms are now more intense, and this trend is projected to continue

• The model information generated by this work is at a spatial scale that is informative for decision making and conforms to weather watch and warning criteria